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RESEARCH ARTICLE

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The role of motor imagery in learning a totally novel movement

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Abstract The aim of the present study is to gain more insight into the mechanisms underlying mental practice. The question of whether a totally novel movement may be learned by mental practice was investigated. Healthy young adults had to learn the abduction of the big toe (dominant right foot) without moving the other toes or the foot. The subjects were divided into two groups: subjects who were absolutely unable to abduct their big toe ("absolute zero" group) and subjects who were able to abduct their toe to some extent but showed clear room for improvement ("already doing it" group). Two separate experiments were executed. In the first experiment, 37 absolute-zero subjects had to practice, mentally or physically, the target movement. In the second experiment 40 already-doing-it subjects had to improve their toe-abduction skill. The results showed that absolute-zero subjects could not acquire the toe-abduction movement by means of mental practice. Only subjects who physically practiced the target movement improved significantly. Subjects who had some experience in the task (already-doing-it subjects) improved significantly after mental practice as well as after physical practice. The results seem to indicate that it is more plausible to explain the learning effects of mental practice in terms of a top-down mechanism based on the activation of a central representation of the movement than in terms of a peripheral bottom-up mechanism based on the activation of muscles.

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Introduction

The term *mental imagery* refers to a topic in skill learning with a long history. Richardson (1969) has described mental imagery as all quasi-sensory or quasi-perceptual experiences that exist in the absence of those stimulus conditions that are known to produce genuine sensory or perceptual experiences (Richardson 1969, pp 2–3). Mental imagery can be performed in different modalities such as visual, auditory, tactile, kinesthetic, olfactory, gustatory, or any combination of these senses. A special subcategory of mental imagery is formed by *motor imagery*, which refers to the internal reproduction of a specific motor action without any overt motor output. *Mental practice* is a training method by which motor imagery is used with the intention of improving performance, in other words it is the imagined rehearsal of a motor act with the specific intent of learning or improving that act.

Several studies have shown that mental practice can be effective in optimizing the execution of movements in athletes. Furthermore, it may help novice learners in the acquisition of new skills. Many of these studies have been reviewed by Feltz and Landers (1983) and Driskell et al. (1994). They show that subjects who mentally trained for a specific task usually displayed less improvement than those who trained physically. However, compared with control subjects who did not practice at all, it could be shown that mental practice, indeed, facilitated performance. Based on the effects of mental practice, some investigators have proposed the use of mental practice in neurological rehabilitation, as it may be a novel and cost-efficient treatment tool (Fansler et al. 1985; Warner and McNeill 1988; Page et al. 2000, 2001).

Despite an established research tradition, the theoretical basis for the effects of mental practice remains hypothetical. Several theories have been proposed to explain the mechanisms by which mental practice may improve motor learning. In the following section, the two most prominent theoretical notions will be shortly discussed: the psychoneuromuscular theory and the central representation theory.

The psychoneuromuscular theory, also called the peripheral theory, is based on the observation that during imagery of a particular movement the same muscles are activated as during overt movement execution (Driskell et al. 1994; Boschker 2001). It is proposed that, when a subject is mentally practicing the execution of a movement, impulses are sent to target muscles. Furthermore, it is suggested that the same neuromotor pathways that are involved in the execution of a specific action are activated also during mental practice. This activation aids skill-learning by improving the appropriate coordination patterns as a result of the strengthening of motor programs in the motor cortex, and by priming the corresponding motoneurons of the muscles necessary to execute a motor task (Mackay 1981; Magill 1998; Page et al. 2001).

The psychoneuromuscular theory is supported by a number of studies. Jacobson (1932) was one of the first to demonstrate an increase in muscular activity when subjects were imagining movements. During movement imagery, however, the magnitude of the activation was only a fraction of the activation that took place during actual performance, and hardly any overt motion was seen. Also more recent studies show an increase in electromyographic (EMG) activity during imagined action (Hale 1982; Wehner et al. 1984; Jowdy and Harris 1990; Bakker et al. 1996; Weiss et al. 1994; Livesay and Samras 1998). In general, these studies indicate that EMG activity is limited to those muscles that participate in the simulated action (Magill 1998; Schmidt and Lee 1999). Furthermore, several studies have found the EMG increase to be proportional to the amount of imagined effort (Shaw 1940; Wehner et al. 1984; Bakker et al. 1996). Bakker et al. (1996), for example, have shown that imaginary lifting of 9-kg dumbbells results in more EMG activity than imaginary lifting of 4.5-kg dumbbells. Hence, it seems that the kinesthetic image of a motion pattern is accompanied by the same innervation pattern as during the motion itself.

However, at the same time, motor imagery experiments have been performed in which EMG activity is absent during movement imagery. Yue and Cole (1992) have compared, in healthy subjects, the maximal voluntary force production of the fifth digits metacarpophalangeal joint after a training program of repetitive, maximal isometric muscle contractions with the force production after a mental training program that did not involve repetitive activation of muscles. The mean abduction force of the left (trained) digit increased 30% for the contraction group and 22% for the imagining group, whereas a control group showed no improvement. Hence, an increase in force was achieved without actual repeated muscle activation. Yue and Cole conclude therefore that the increase in muscle strength following mental training could not be the result of neural changes at the execution level, but had to be attributed to higher (central) levels of the motor system involved in planning and programming.

Jeannerod (1994) has explored the idea of a central control theory further. He argues that actions are driven by an internally represented goal rather than directly by the external world. He assumes that motor imagery is part of the motor representation and related to intending and preparing movements. Motor representations are conceived as internal models of the goal of an action, whereby the goal is defined as the final result at which the action is intended (Jeannerod 1995). Although motor preparation is an entirely nonconscious process, the content of motor images can be accessed consciously. It seems that motor images are endowed with the same properties as those of the corresponding motor representation, that is, they may play the same causal role in the generation of a movement (Jeannerod 1995).

In the last few years, a growing number of studies have shown that many neuropsychological and physiological similarities exist between physically executed and imagined movements (Decety et al. 1991, 1993; Jeannerod 1994; Jeannerod and Decety 1995; Hall et al. 1995; Pascual-Leone et al. 1995; Decety 1996; Decety and Grèzes 1999; Lotze et al. 1999; Jackson et al. 2001; Hanakawa et al. 2003). Pascual-Leone et al. (1995), for example, have examined changes in functional brain organization after mental practice. Subjects had to execute a one-handed piano exercise for 5 days. The results showed that the size of the contralateral output map for the long finger flexor and extensor muscles increased progressively each day as the subjects practiced the task. The increase in size of the representation was equivalent in both physical and mental training conditions. The level of performance in the mental-practice condition after 5 days was equivalent to that of the physical-practice condition after 3 days. After adding 1 physical training session at the end of a period of 5 days of mental practice, subjects reached the same level of performance as those who were in the physical training group. It seems, therefore, that mental practice has a preparatory effect on the task, which increases the efficiency of subsequent physical training.

Furthermore, positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) show that the cortical regions involved in the execution of a movement are also active during motor imagery. Lotze et al. (1999) have studied brain activation during executed and imagined movements of the right and left hand using fMRI. They have found that the supplementary motor area (SMA), the premotor cortex (PMC), and the primary motor area (M1) are equally activated during both actual and imagined movement. The SMA and PMC play a prominent role in the planning, generation, and execution of more complex motor tasks (Abbruzzese et al. 1996).

The aim of the present study is to gain more insight into the mechanisms underlying mental practice. Therefore we focus on the question whether a totally novel movement can be learned by mental practice. Recall that the psychoneuromuscular theory claims that mental practice can be explained in terms of a bottom-up effect. Mental practice leads to peripheral activity, which provides afferent information to the motor cortex in order to strengthen the motor program. If this notion is correct, totally novel movements also can be learned by mental practice. Indeed, every imaginary movement will lead to subtle increases in the activity of the involved muscles. The central representation theory, however, claims that the learning effects of mental practice may be explained in terms of a top down effect or a central regulation. Actions are driven by a centrally stored movement representation. Without earlier experience in the execution of the target movement, however, no representation is available. Thus, if this central view is correct, a totally novel movement cannot be learned by mental practice.

Two experiments were performed to answer the question. Healthy adult subjects had to learn a totally novel movement, i.e., the voluntary abduction of the big toe of the dominant right foot without moving the other toes or the total foot (Mulder and Hulstijn 1985a, 1985b). The subjects were divided into two groups: subjects who were absolutely unable to abduct their big toe, who were termed the absolute-zero subjects, and subjects who were able to abduct the toe, but showed ample room for improvement, the already-doing-it subjects. In the first experiment, the absolute-zero subjects had to practice, mentally or physically, the target movement. In the second experiment, the already-doing-it subjects had to improve their skill. If the central representation theory is correct, the absolute-zero subjects will profit from physical practice but not from mental practice, since no stored movement representation can be activated by imagery, whereas the already-doing-it subjects will be able to improve their skill also by mental practice. If the peripheral approach is correct, it is expected that also the absolute-zero subjects will profit from mental practice and that noticeable peripheral activity can be registered during mental practice.

Experiment 1

Method

Subjects

Thirty-seven right-footed individuals, aged 19–35 years, with no history of foot-related diseases participated in the study (12 men, 25 women). Most of them were university students. All were unable to abduct their big toe and therefore called *absolute-zero subjects*. The study was approved by the local ethics committee. All subjects gave written informed consent.

Procedure and apparatus

The experiment started with a pretraining measurement, 1 week before the training sessions started. The ability to abduct the big toe voluntarily, as well as the imagery ability and the foot dominance were determined. The ability of mental imagery was assessed by the Vividness of Movement Imagery Questionnaire (VMIQ; Isaac et al. 1986). The VMIQ consists of 24 items reflecting the internal standpoint and 24 items reflecting the external standpoint. The internal standpoint refers to the ability of a subject to imagine that he/she performs the movement, in contrast to the external standpoint, which refers to the ability of a subject to imagine that somebody else is performing the movement. In the present study only the internal imagery items were employed. A score of 72 or less on the internal imagery items was required to be included. The used cut-off point was based on the following rationale: all 24 items for the internal standpoint had to be scored with a 3 (moderate capacity to imagine the performance of a movement), a 2 (a good capacity to imagine movement performance), or a 1 (excellent imagination of the movement performance as lively as actual performance). Scores of 4 (a vague and unclear image) or 5 (no image at all) were not accepted. The four subjects who scored higher than the cut-off point were excluded.

Foot dominance was assessed by the Waterloo Footedness Questionnaire—Revised (Elias et al. 1998), and abduction of the big toe was determined by measuring the range of motion (ROM) twice. Only right-footed subjects with a ROM of zero degrees in both measurements, indicating a total inability to abduct the big toe, were accepted. Subjects with (even minimal) voluntary control were excluded. The ROM was measured with the subjects sitting in a chair, their knees flexed approx. 120°. Both feet were resting on a sheet of paper. In order to stabilize the right foot, two laths were fastened on the floor in an angle of 90°; the heel and the lateral side of the foot had to be pressed against these laths. The resting position of the big toe was measured by tracing a straight line along the medial side of the right big toe and the first metatarsal phalangeal joint. Subsequently, subjects were asked to abduct the toe as far as possible, without moving the whole foot or the other toes. A second line was traced and the angle between the first and the second line was considered as the ROM of that measurement.

The included subjects were randomly assigned to one of three groups: (1) a group (n=14) receiving mental practice (MP); (2) a group (n=11) receiving physical practice (PP); and (3) a control group (n=12) receiving no practice at all (CG).

The subjects in the MP and PP groups received two training sessions on 2 successive days. Each training session consisted of 10 trials of 1 min. The individual trials were interspersed with rest periods of 30 s. After 5 trials the subjects were allowed to rest for a period of 5 min. During a session subjects had to mentally or physically practice the abduction of the right toe.

Subjects in the PP group had to attempt to abduct their big toe. In each session, during 10 trials of 1 min each, they had to attempt to move their big toe outward. Subjects were free to choose the frequency of abducting attempts, but a minimum of 10 repetitions in every trial was required. During practice they were allowed to visually control their attempts. Subjects in the MP group had to close their eyes and were instructed to imagine themselves moving their big toe outward. They could choose between closing the eyes or being blindfolded. The abduction of the big toe had to be imagined as vividly as possible. Subjects should almost feel their big toe moving, but actual movement of the toe was not allowed. They had to imagine moving the toe in the same rate as subjects in the PP group, that is, during 10 trials of 1 min each, they had to imagine toe movements for a minimum of 10 attempts per trial. The subjects in the CG only underwent the pre- and postmeasurements.

Main target of the training sessions was to increase the ROM. The ROM of subjects who physically practiced the movement, was measured before and after each session. To prevent interference with physical practice, the ROM of subjects in the mental practice group was only measured before session 1 and after session 2 (postmeasurement). The postmeasurements for all groups took place immediately after ending training session 2.

EMG

To observe whether peripheral activity was present during mental practice, EMG activity of the m. abductor hallucis of the right foot was recorded during the first 30 s of trial 3, 4, 8, and 9 of each training session. During each training session, EMG activity at rest

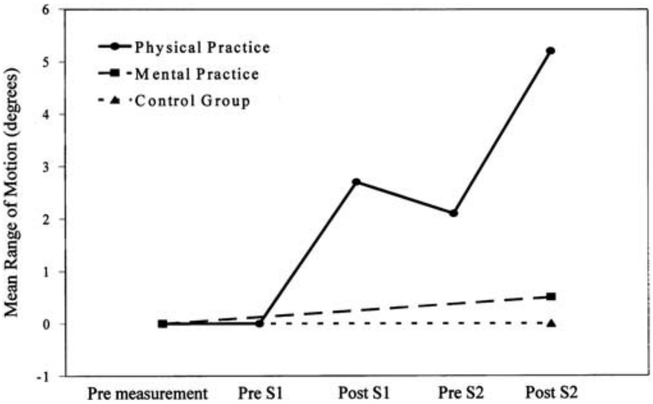

Fig. 1 Mean range of motion (ROM) scores of the absolute-zero subjects, measured on the pre- and posttests of sessions 1 and 2 (*S1, S2*) and on the preexperimental measurement 1 week before the experiment started

was measured within the first 10 s of trials 3 and 8. To determine possible bilateral effects, the EMG activity of the left foot was also measured. Surface EMG signals were recorded bipolarly by ConMed 1720 disposable, surface silver–silver chloride electrodes, with a diameter of 10 mm (ConMed, Utica, N.Y., USA). The electrodes, with custom-built preamplifiers (×1,500) directly mounted on the electrodes, were placed on the surface of the belly of the m. abductor hallucis. The interelectrode distance was 20 mm center-to-center. In order to assure the same location of the electrodes across the two sessions, the electrode position was marked on the skin. The subjects received no feedback about the level of EMG output of the target muscle. The rectified EMG signal was band-pass filtered 20 Hz to 10 kHz and rectified and smoothed with a time constant of 25 ms. Subsequently, the signal was further processed and filtered with a Butterworth 1-Hz filter of the second order. The median of maximum peak EMG activities was determined.

Statistics

Paired *t*-tests were used to determine whether subjects in a specific group improved the abduction of the big toe after training sessions. A one-way ANOVA was used to determine whether groups differed from each other in improvement of ROM. Finally, post hoc multiple comparisons assessed which groups differed significantly from each other. All tests were performed with a 95% reliability interval.

Results

None of the subjects were able to abduct the right big toe voluntarily during the premeasurement session. All subjects were therefore equal at the start of the experiment. A one-way ANOVA was performed to assess whether the three groups improved differently on the abduction of the big toe. The test showed a significant difference in improvement between groups ($F_{2,\ 34}$=147.93, P<0.001). Post hoc multiple comparisons showed that subjects in the PP group scored higher on the ROM measurements after the training sessions than subjects in other groups. They improved significantly more than the subjects in the other groups (Bonferroni and Scheffe: P<0.001). Table 1 shows the mean ROM scores of the groups.

Paired *t*-tests showed that subjects in the MP group and the control group, in contrast to the PP group, did not significantly improve their toe-abduction skill. Moreover, the CG and MP group did not differ from each other concerning the ROM scores. The mean ROM scores of the groups are presented in Fig. 1. Subjects in the PP group improved initially in session 1 (mean 2.7°), but most improvement was shown during session 2 (mean 3.0°). However, this difference was not significant.

Experiment 2

Method

Subjects

The experiment was basically the same as experiment 1. The main difference with the previous experiment was that only *already-doing-it subjects*, that is, subjects who were able to abduct their big toe to some extent, were included. Forty subjects aged 19–35 years (16 men and 24 women), most student volunteers, participated in the experiment. Criteria for inclusion were the same as in experiment 1. Thirteen participants were randomly assigned to the MP group, 14 subjects to the PP group, and 13 to the control group. The study was approved by the local ethics committee.

Procedure and apparatus

The same apparatus and procedure were used as in experiment 1. Main target of the training sessions was to improve the voluntary maximal abduction of the right big toe.

EMG

The results of experiment 1 showed no EMG activity in the m. abductor hallucis of the left toe during practice. Therefore, only EMG activity in the m. abductor hallucis of the right foot was measured.

Statistics

The same analysis was used as in experiment 1. A one-way ANOVA was used to determine whether the groups were equal at the start of the experiment.

Table 1 Differences in range of motion (*ROM*) of absolute-zero subjects at pretest session 1 and posttest session 2

Group		Start of training		End of training		ROM			
	N	Mean ROM	SD	Mean ROM	SD	Post−pre	*df*	*t*	*P*
Mental practice	14	0	0	0.5	1.1	+0.5	13	−1.47	0.17
Physical practice	11	0	0	5.7	0.9	+5.7	10	−20.89	0.00
Control	12	0	0	0	0	0	NA	NA	NA

NA, not applicable

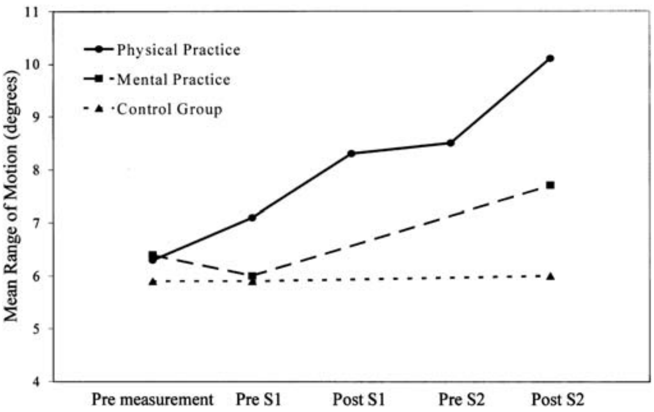

Fig. 2 Mean ROM scores of the already-doing-it subjects, measured on the pre- and posttests of sessions 1 and 2 and on the preexperimental measurement 1 week before the experiment started

Results

No significant differences in ROM scores existed between the groups at the pre measurement of session 1. Therefore the groups were equal at the start of the experiment. A one-way ANOVA determined significant differences in improvement of ROM between groups after training sessions ($F_{2,\ 37}$=13.70, P<0.001). Table 2 presents the improvement of subjects in the three different groups.

Subjects in the PP group as well as in the MP group were able to improve their capacity to abduct the big toe significantly after the two training sessions. Post hoc multiple comparisons showed that, compared with the control group, improvement in ROM was significantly higher in the PP group (Bonferroni and Scheffe, P<0.001) and MP group (Bonferroni and Scheffe, P<0.05). In spite of seemingly less improvement in the MP group, the difference between the PP and MP group was not significant. Subjects in the CG group showed no significant improvement at all. Figure 2 presents the mean ROM scores of the groups across the training sessions.

EMG activity in both experiments

During training sessions no EMG activity could be observed in the m. abductor hallucis of the right foot of subjects in the MP group. Also, in the left foot of the subjects in the PP and the MP groups, no EMG activity was measured. Only physical practice caused noticeable EMG output.

Discussion

Two theoretical notions were mentioned, the psychoneuromuscular theory and the central representation theory. If the psychoneuromuscular theory would be valid, it was expected that even novice learners, the absolute-zero subjects, would be able to learn a totally novel movement by means of mental practice, since mental practice would lead to activation of the involved target muscle. However, in both experiments no EMG activity in the m. abductor hallucis of the right as well as the left foot could be obtained during mental practice. Furthermore, the results of experiment 1 showed that only subjects who physically practiced the task improved their ability to abduct the big toe voluntarily. The absolute-zero subjects, who mentally practiced the task, did not improve. In experiment 2 all subjects who practiced the target movement improved their toe-abduction skill. Physical practice as well as mental practice led to improvement.

Hence, the results seem to indicate that it is not possible to explain the effects of mental practice in terms of a bottom-up mechanism. Indeed, it seemed that the subjects in the MP groups did not receive any information from target muscles. Neither does it seem plausible that the failure of the MP group in experiment 1 to improve their toe-abduction skill was due to the fact that the training sessions were too short. Most studies report training periods shorter than the 20 min we employed in our experiment (see Feltz and Landers 1983; Driskell et al. 1994). Driskell et al. (1994) and Feltz and Landers (1983) have found the largest effects after interventions of approximately 20 min. Therefore, the length of the training sessions in both experiments should be long enough to show at least some improvement.

It seems, therefore, more plausible to explain the effects of mental practice in terms of a top-down mechanism. Recall that the central representation theory would predict that absolute-zero subjects would profit from physical practice but not from mental practice, since no stored representation could be activated. Only subjects with some experience in the task would be able to improve their skill. The results seem to support this expectation. Indeed, only the already-doing-it subjects profited from mental practice. After two training sessions, they were able to improve the abduction of their big toe significantly, whereas subjects without knowledge of how to execute the movement (absolute-zero subjects) were not able to improve the abduction movement by means of mental practice.

The results of the present study are in line with the findings of Yue and Cole (1992) as mentioned in the Introduction. Recall that they argue that the obtained

Table 2 Differences in ROM of the already-doing-it subjects at pretest before session 1 and at posttest after session 2

Group		Start of training		End of training		ROM			
	N	Mean ROM	SD	Mean ROM	SD	Post-pre	*df*	*t*	*P*
Mental practice	13	6.0	2.6	7.7	2.8	+1.7	12	–4.95	0.00
Physical practice	14	7.1	2.7	10.1	3.0	+3.0	13	–5.84	0.00
Control	13	5.9	1.5	6.0	1.6	+0.1	12	0.47	0.65

training results after mental practice cannot be attributed to neural changes at the execution level, but should be explained in terms of changes at the planning and programming level of the motor system. Hence, it seems that mental practice leads to improvement only when a representation of the target movement is present. In other words, the data suggest that motor imagery results from the utilization of stored representations of action. As Crammond (1997) has argued, motor imagery is something other than creative imagination.

The absolute-zero subjects were not able to use motor imagery for improving toe abduction because they did not have a representation for that movement. That makes them different from patients who, due to a lesion, are no longer able to perform specific movements but very often retain the ability to imagine these movements accurately (Johnson 2000; Johnson et al. 2002).

The conclusion that we can mentally train only those movements that we have performed before is important, because it may restrict the use of mental practice in neurological rehabilitation and sports to movement categories that have been performed earlier.

There is a final problem that deserves discussion. The problem refers to a more or less fundamental pitfall in motor imagery. Indeed, after the instruction to imagine a certain movement, no possibility exists to control whether subjects are doing what you ask them to do. This, indeed, is a peculiar situation for experimental research, where the dependent variable has to be controlled as rigidly as possible.

This methodological shortcoming, however, should not be overrated, since a substantial number of neuroimaging studies show that motor imagery results in the activation of brain areas that are directly related to the imagined movement, so that we have some certainty that the instruction to imagine a movement, indeed, leads to the desired cognitive act (see Jeannerod 1994; Naito et al. 2002; Gerardin et al. 2000; Crammond 1997; Porro et al. 1996)

The present experiments deliver further evidence for the hypothesis that imagery and movement execution share common neural mechanisms. Indeed, the improvement of the toe-abduction movement by motor imagery in the already-doing-it group without activating the target muscle underscores the role central mechanisms may play in bringing about this result. The absence of any peripheral activation seems to rule out a completely neuromuscular or afference-based peripheral explanation. This preliminary conclusion, however, has to be tested in further studies.

This study should be read as a modest attempt to unravel the underlying causal mechanisms of mental practice. Much, however, remains unclear. Future research should be focused on finding more evidence for a central control mechanism. An interesting next step is to answer the question of whether the acquired toe-abduction skill would generalize to the left (untrained) foot as would be predicted when mental practice leads to the strengthening of a motor program. Brain-mapping techniques seem necessary to gain more insight into the differences in cortical activation between the absolute-zero subjects and already-doing-it subjects and how the cortical activation changes during (mental) practice sessions.

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